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L.F./M.F. RADIO-DATA: mush-area reception tests

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Research Department, Engineering Division
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Summary

Programme-compatibility reception tests of a proposed data-transmission system for l.f. radio broadcasting are described. The tests demonstrate that the proposed system, which employs carrier phase-modulation, is compatible with programme reception in the "mush-areas" between co-channel, co-programme stations, provided that the data signals radiated from the stations are identical and "delay-equalised" to arrive in the mush-area in synchronism. Data reception tests were also carried out which indicate that if programme compatibility is achieved, data reception is also feasible.

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L.F./M.F. RADIO-DATA: MUSH-AREA RECEPTION TESTS

M.E. Bailey, B.A.

1. Introduction

The Report considers a subliminal signalling system for l.f. and m.f. broadcast transmissions using phase-modulation (p.m.) to provide a data signalling rate of up to 25 bits per second. A companion Report[1] describes the evolution of the basic signalling parameters. The parameters were chosen in the light of the requirements of compatibility with programme reception and ruggedness of data reception, whilst maximising the data rate. The limiting factor in the choice of parameters is the effect of the transmission's own sky-wave signal at the limit of the service area which, because it is delayed relative to the groundwave signal, can cause phase-modulation to amplitude-modulation (p.m.-to-a.m.) conversion and thus make the data signal audible as a rumble in the background of the programme[1]. This effect was found to limit the peak phase-deviation to 11.25 degrees at a data rate of 25bit/s for general l.f. or m.f. use, although the effects of sky-wave interference are expected to be worse at m.f. than at l.f., where higher values of deviation may be possible.

A service may sometimes be provided most efficiently by the use of several transmitters operating on the same frequency as a so-called synchronised group. In such a common-frequency transmitter network, there exist areas between the stations in which the signal strengths from two or more are comparable and mutual interference can result. These areas are known as "mush-areas". Means for reducing the interference by "audio modulation delay equalisation", that is ensuring that the audio programme modulations carried by the two signals arrive in synchronism in the mush area[2], and synchronisation of the phases themselves[3] are now well known. However, the introduction of data signal phase-modulation on one or both of the carriers can be a further source of interference. This is because the presence of the phase-modulation can give rise to p.m.-to-a.m. conversion, just as with sky-wave interference, and thus make the data signal audible to the listener. However, this form of interference can be reduced by delay-equalising the data signal modulations so that they arrive in synchronism in the mush-areas, in the same way as the programme signal modulation. The purpose of the reception tests described in this Report was to determine the effectiveness of such a measure in practice and to determine the timing tolerances required to implement suitable modulation delay equalisation for the Radio-4 (U.K.) 200 kHz synchronised group.

2. Mush-Area Interference

The Radio-4 (U.K.) service is provided by three 200 kHz transmitters at Droitwich, Westerglen and Burghead, as shown in Figure 1*. The transmitters radiate a vertically-polarised electric field component. There are two mush-areas between the stations shown shaded in Figure 1: a southern mush-area, around Carlisle and Newcastle, and a northern mush-area, roughly mid-way between Westerglen and Burghead. In this Report, only the southern mush-area is considered in detail, since similar conditions apply to the northern areas and similar conclusions will apply.

Consider first the case of a two-transmitter common-frequency network. A single mush-area will exist in the region between the transmitters where the signal strengths from each are comparable. Without audio modulation-delay-equalisation or carrier phase-synchronisation, the extent of such a mush-area is normally defined as that area inside which the ratio of the received field strengths is 9 dB or less[2]. A field-strength standing-wave pattern is set up between the transmitters and, within the mush-area, wide variations in the value of the resultant field-strength will occur. In particular, along the contour of equal field-strengths, there will be electric-field cancellations and no signal will be received in such places using a truly omnidirectional electric aerial. Thus it can be seen that the field-strength in the mush-area has both a coarse structure (the gradual variation of the ratio of the two carrier levels) and fine structure (the standing-wave pattern of interference between them).

The standing-wave pattern is only truly stationary when the carriers are locked in phase and this is beneficial[4], as described in Section 2.1. The Radio-4 (U.K.) l.f. service uses transmitters that are carrier-phase-synchronised[3] and this condition will be assumed in the rest of this Report.

Listeners in the mush-area can suffer poor reception simply due to insufficient signal strength in areas of near cancellation and this is inevitable with a co-channel network of this kind. Far more disturbing, however, is the distortion and interference that is caused when the modulations on the

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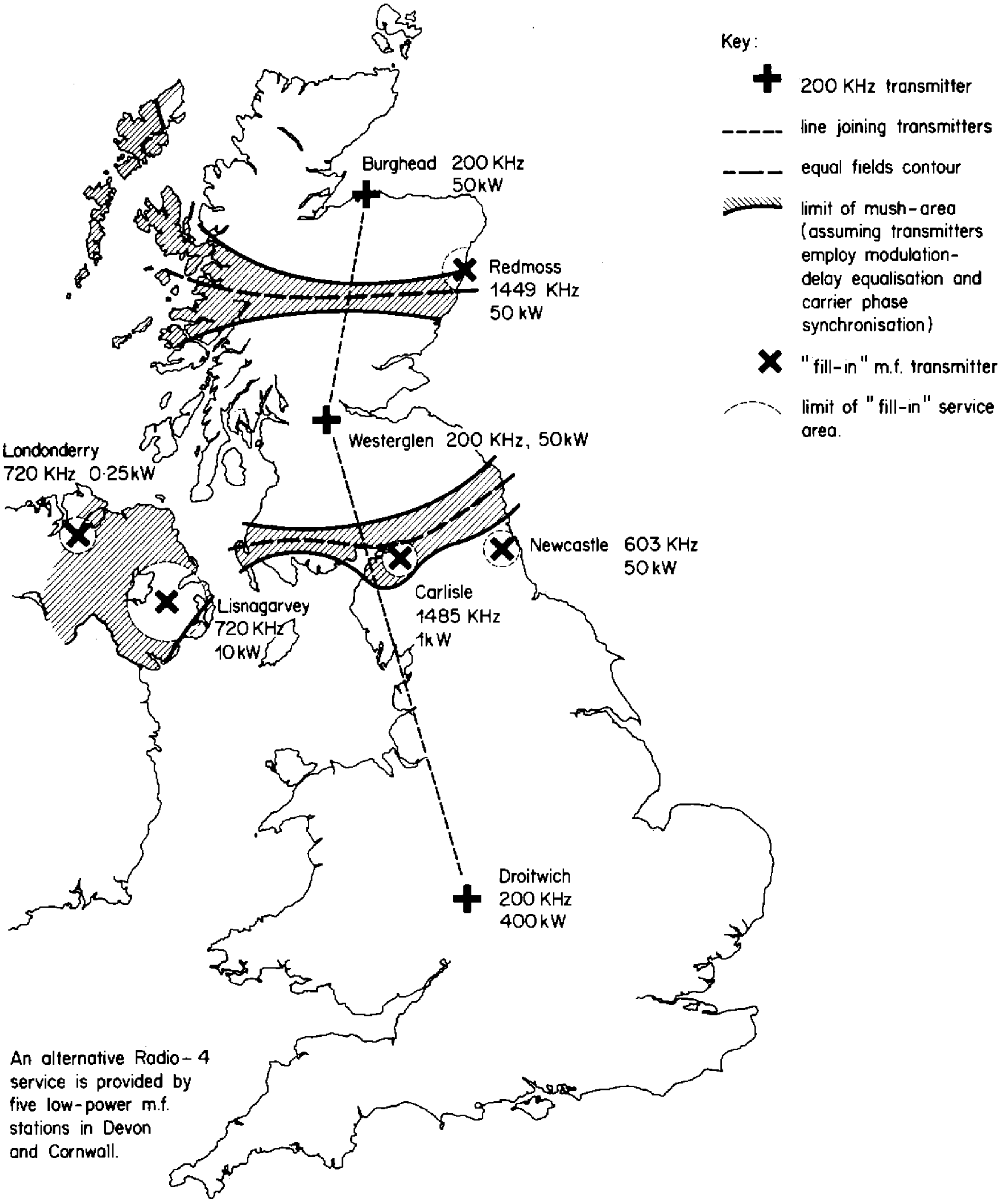
* Figure 1 was prepared using data provided by Mr. C.P. Bell.


Key:
200 KHz transmitter
line joining transmitters
equal fields contour
limit of mush-area (assuming transmitters employ modulation-delay equalisation and carrier phase synchronisation)
"fill-in" m.f. transmitter
limit of "fill-in" service area.
Burghead 200 KHz 50kW
Redmoss 1449 KHz 50 kW
Westerglen 200 KHz, 50kW
Londonderry 720 KHz 0·25kW
Newcastle 603 KHz 50kW
Carlisle 1485 KHz 1kW
Lisnagarvey 720 KHz 10kW
Droitwich 200 KHz 400kW

An alternative Radio-4 service is provided by five low-power m.f. stations in Devon and Cornwall.

Figure 1. The coverage of the 200 kHz Radio-4 (U.K.) service.

two carriers differ. Without considering the effect of data signal phase-modulation, the modulations will generally differ mainly due to different delays and dispersion on the two paths from the studio through the first transmitter, and from the studio through the second transmitter to the receiver, unless special steps are taken by "delay-equalising" the modulations[2]. The resulting distortion of the received programme signal is very objectionable and is greatest when the carriers are near to cancellation. In Figure 2, the two carriers are represented by vectors and are shown in the condition of near-cancellation. When both carriers carry identical amplitude-modulations, the resultant carrier will also be identically modulated, since the vector triangles formed by the two vectors and their resultant will remain geometrically "similar" throughout the modulation cycle. When one of the modulations differs in any way from the other, the similarity no longer holds and the modulation of the resultant is a distorted version of the original; over-modulation often occurs, leading to gross distortion after envelope-detection. This distortion aggravates the already poor signal-to-noise radio due to the low signal-strength. Because its severity depends on the nearness to cancellation of the received signals, it is clearly both aerial and location dependent.

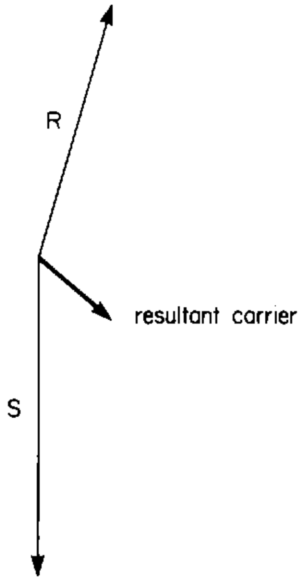


Fig. 2 - Addition of two carriers without phase-modulation.
R first, carrier (reference)
S second carrier.

Assuming that perfect audio-modulation delay-equalising is in operation, consider now the addition of phase-modulation to one or both of the carriers. Figure 3 shows the effect on the resultant. Here, Vector R represents one carrier that is not phase-modulated. The second carrier S is phase-modulated and the resultant carrier is thereby modulated in both phase and amplitude; the amplitude modulation may be heard as interference. For the data transmission parameters used here, the interference may be heard as a low-frequency rumble (additive interference) although, in cases of gross distortion, the data signal can be heard to modulate the received programme signal (multiplicative interference). Alternatively, Vector S can be thought to represent the relative or difference in phase-modulation compared with the reference R. Clearly, interference-free reception is obtained when the two phase-modulations are identical in both timing and deviation.

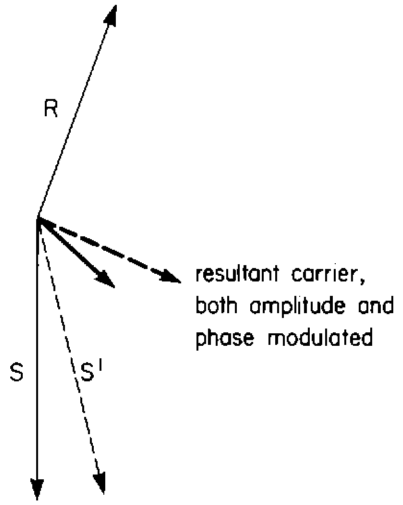


Fig. 3 - Addition of two carriers, one of which is phase-modulated relative to the other.
R first, carrier (reference)
S second carrier in one phase-modulation extremity
S' second carrier in other phase-modulation extremity.

Perfect delay-equalisation occurs on the locus of equal modulation-timings and can thus, at best, be achieved only along a very narrow band or line through the mush-area. It is usual to arrange for this line to coincide as nearly as possible with the equal field-strengths contour where mush-area distortion is worst. The purpose of the field tests described in this Report was to ascertain how exact the delay-equalisation needed to be for data-signal phase-modulation to preserve programme compatibility.

2.1. Choice of receiving aerials

The choice of receiving aerial is pertinent to the analysis of mush-area interference, firstly due to any directional properties of the aerial and secondly due to whether the aerial responds to the electric or magnetic field component. Directional properties can sometimes be used to favour one transmission rather than the other; one exception is the use of an aerial with a 'figure-of-eight' polar diagram located on or near to the line joining the two transmitters. The electric field, which is vertically polarised in this case, has been considered above. However, the magnetic field components from the two transmitters are horizontally polarised and, except on the line joining the two transmitters, can never cancel due to their geometry, as shown in Figure 4.

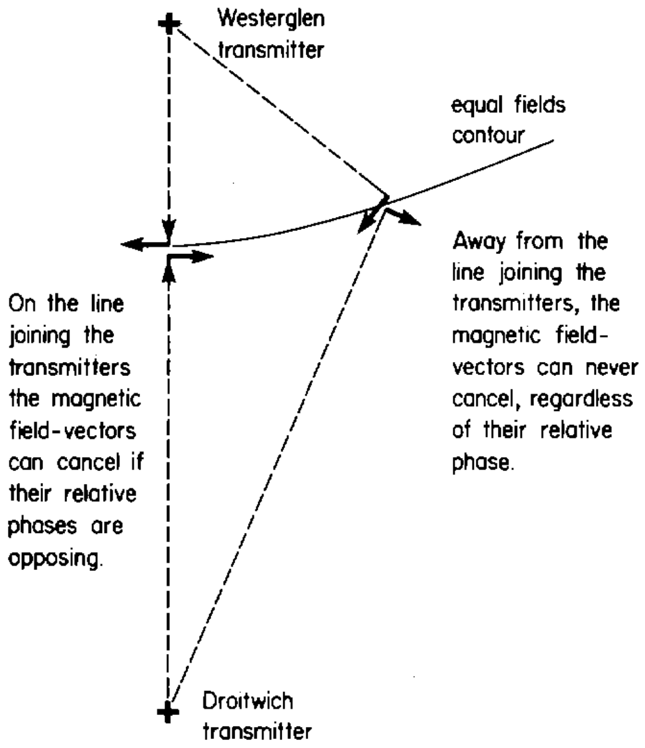

Westerglen transmitter
equal fields contour
Away from the line joining the transmitters, the magnetic field-vectors can never cancel, regardless of their relative phase.
On the line joining the transmitters the magnetic field-vectors can cancel if their relative phases are opposing.
Droitwich transmitter

Fig. 4 - The addition of the two magnetic-field vectors in a two-station mush-area

The majority of medium-wave and long-wave receivers use ferrite-rod aerials, which responds directionally to the magnetic field component. Thus, with reference to Fig. 4, it will be seen that such receivers can always pick up a signal if they are correctly orientated, and are not located on the line joining the transmitters. It is to enable the orientation of receivers to be optimised and thereafter left undisturbed, that the transmitters are carrier-phase synchronised.[4]

Whip aerials, as used in cars, cannot benefit in this way both because they respond to the electric field component, and because they are generally in motion, so that all parts of the standing-wave pattern in the mush-area are explored, and directional car aerials could not usefully be employed in any case. For this reason whip aerials were not used in any of the tests, except for limited experiments to verify the above statements.

2.2. The effect of the third, co-channel transmitter

The 200 kHz Radio-4 (U.K.) network is in fact made up of three carrier-phase synchronised transmitters, as shown in Figure 1, and there are consequently two mush-areas. In each mush-area, the signal due to the third, weakest station is small but nevertheless not negligible, a typical figure applicable to the centre of either mush-area being about 15 dB below either main signal alone. The effect of the third signal is to modulate the fine standing-wave structure, whilst not affecting the overall coarse structure. As Figure 5 shows, the third signal, though small, can modify what would otherwise have been a near cancellation of the two main carriers to either increase or decrease the magnitude of the resultant depending on the relative phase of the third signal. Thus, in practice, regions can be found close to the equal-fields contour (for the two main signals) where very deep electric field minima are observed, whilst a few wavelengths away the minima are not so deep. Moreover, in areas where the main signals are dissimilar, cancellations can now occur, as shown in Fig. 5(d).

The effect is illustrated in Figure 6 gives a plan view of the field-strength distribution over a small area near Carlisle(but not including the equal-fields contour) when:-

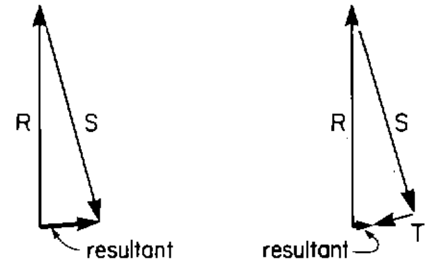
a) the signals from only Droitwich and Westerglen are considered, and

b) the signals from all three transmitters are considered.

The field strength distributions were prepared using a computer program which assumed an inverse distance variation of field strength. In the first case, a simple standing-wave pattern is created, the troughs of which are virtually straight and of constant depth. The addition of the third transmitter in (b) causes a perturbation of the standing-wave pattern in which the troughs are modulated slightly in shape and particularly in depth.

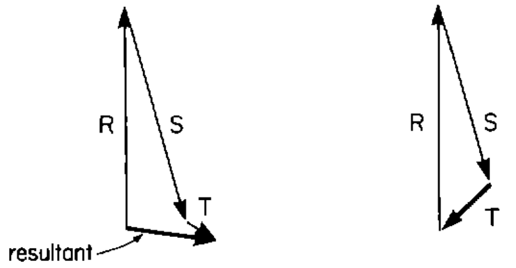
2.3. Problems encountered in surveying mush-area interference

The coarse and fine structure of the



(a) showing the resultant when T is not considered

(b) with T in one phase



(c) with T in another phase

(d) with T causing cancellation

Fig. 5 - The effect of a third carrier on two main carriers in a mush-area

R first, reference carrier
S second carrier
T third carrier with magnitude smaller than R or S

mush-areas, together with the choice of receiving aerials and the effect of the third transmitter, all complicate the analysis of mush-area interference. In order to obtain meaningful results, it is necessary either to carry out a listening survey involving a very large number of reception locations to ensure that the various degrees of freedom are statistically covered or, once knowing the distribution of such reception conditions, to analyse the reception in a smaller number of locations typical of the others.

In the listening surveys described in this report, both methods were used. Initially it was required to obtain quickly an indication of the worst-case interference caused by the data signal phase-modulation. To save time, no analysis was carried out on the effect of the third (distant) station. Instead, a large number of receiving locations (about 200) were used. The results of this survey were used as a basis for the second survey, in which all three transmitters were phase-modulated and the effects of the third station, of the receiving aerial arrangement, and of mis-timing the otherwise identical phase-modulations from the three stations could be investigated in more detail, though at fewer locations.

3. The mush-area tests

As already stated, the aim of the tests was to establish the compatibility of the proposed data phase-modulation system[1] in mush-area reception. In addition, it was found possible to test the reception of the data signals in the mush-area as described in Section 3.3.2.

In order to carry out the tests, it was necessary to instal phase-modulation equipment at each of the three transmitters, with the facility for transmitting coherent phase-modulation for all three stations simultaneously. Since it was desired only to assess feasibility at this stage and not to set up a working system, it was decided to employ "dead-reckoning", rather than use land-lines to provide and synchronise the signals from the three stations. The method is described below.

3.1. The provision of the data modulation signal

The modulation parameters used in the surveys were those previously established as a result of laboratory tests[1] and proven in the field during some auxiliary data reception trials organised by the Electricity Supply Industry[5]. The data format used in both the data reception trials and the compatibility surveys may, be modified for future use, but this will not affect the results described in this report which are dependent more on the basic modulation parameters.

Briefly, the binary data was arranged in 50-bit frames, each of which consisted of a frame alignment word (occupying 4 bit-cells), six 6-bit data-characters and a 10-bit cyclic redundancy check (C.R.C.) word. Frames were transmitted

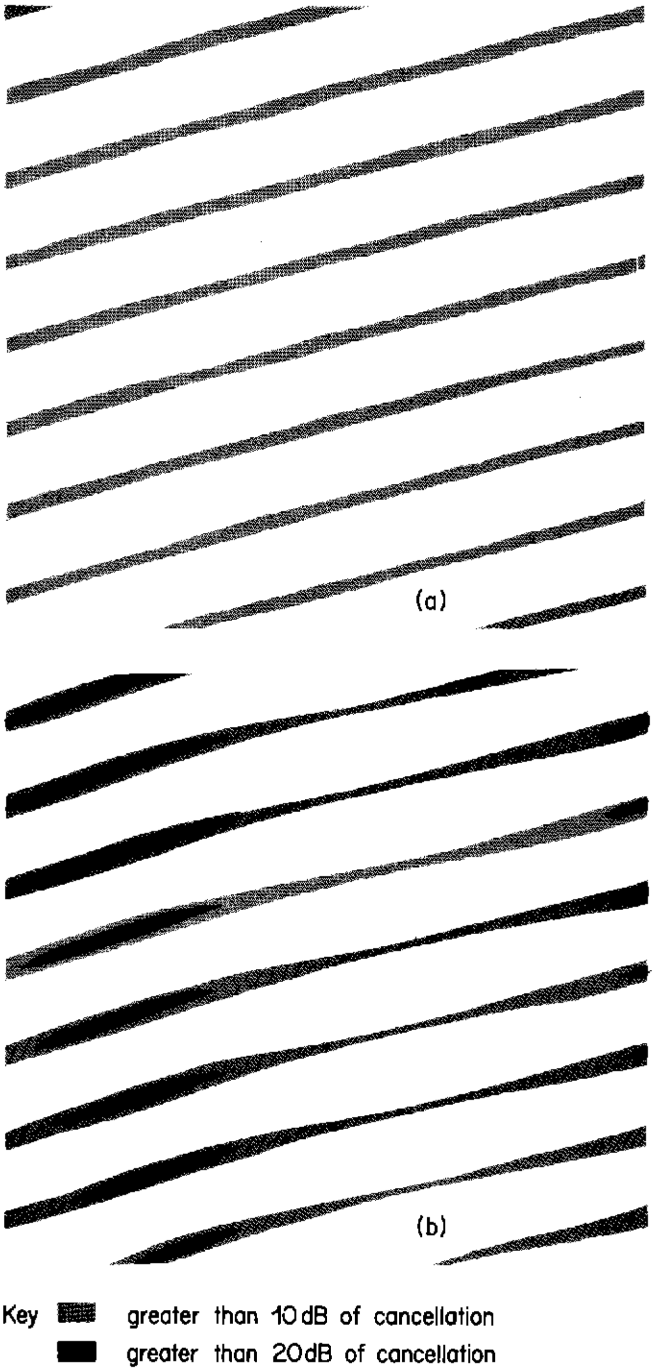

(a)
(b)
Key ▨ greater than 10dB of cancellation
■ greater than 20dB of cancellation

Fig. 6 - The effect of the third transmitter on the mush-area standing wave pattern.

(a). two transmitter operation (b). three transmitter operation

sequentially at a rate of one very two seconds, resulting in a bit-rate of 25 bit/s. The 25 bits-per-second signal was biphase-L coded and subjected to filtering so as to achieve a 50% cosine roll-off response overall (including specified filtering in the receiver). This signal was used to phase-modulate the 200 kHz carrier to a peak deviation of 11.25 degrees. The source filtering ensured that the spectrum of the modulating signal was curtailed at frequencies above 37.5 Hz; moreover, since biphase coding was used, the spectrum did not extend down to zero-frequency, thus preserving the integrity of the 200 kHz transmissions as a frequency standard.

A photograph of the experimental source equipment used at each of the three transmitters in the network is shown in Figure 7. It consisted of a message-processor to generate the modulating waveform, modulation filters, a digital modulator[6], and a system monitor which automatically switched the whole equipment out of service if any malfunction was detected. The message-processor was microprocessor based and generated one of four predetermined sequences of binary data for phase-modulation. Each sequence lasted for twelve minutes, after which the sequence was repeated or another started, as selected via the front panel controls. The phase-modulating equipments installed at the transmitters were substantially identical, and the timings of the data modulations were controlled by the use of a clock* based on the highly stable rubidium frequency-reference providing the r.f. drive to each transmitter. A fourth, mobile rubidium reference was used to set initially the clocks at the three transmitters and later to check their accuracies. A timing accuracy of better than ± 20 μs with respect to mobile clock was achieved over the period of the survey (one week); as will be seen, this was very much more than adequate for the purpose.

The four modulation sequences used are summarised in Figure 8. Each sequence started with a period of no phase-modulation, as a control, followed by an identification signal which was different for each transmitter, thus enabling the survey team to check the presence of modulation on each transmission in turn, using a data receiver in the mush-area. After the identification period, there followed about seven minutes of continuous phase-modulation during which the relative timings of the modulations from each station could be altered by selecting the appropriate sequence, as listed in Figure 8. In addition, the overall modulation timing offset for each station could be set up precisely on the message-processor. In this way, the effect of changing the relative timings of otherwise identical phase-modulations as received in the mush-area was investigated. It should be noted, of course, that

* Throughout this Report, the term "clock" is used to describe one of a number of identical timepieces which were initially synchronised at the beginning of the field tests and gave a measure of elapsed time in fractional parts of a twelve-minute sequence. Five clocks were used in all - one at each transmitting station one in the survey vehicle and one mobile "master clock" which was periodically used to check the calibration of the others.

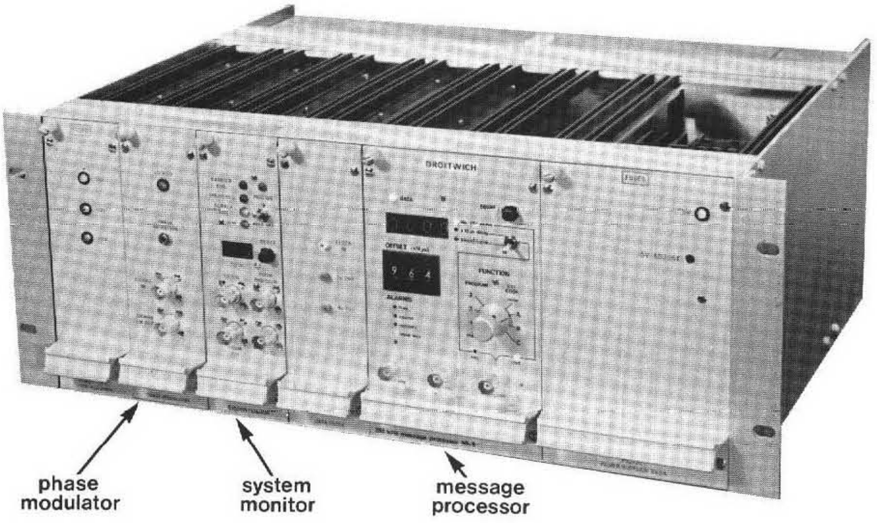
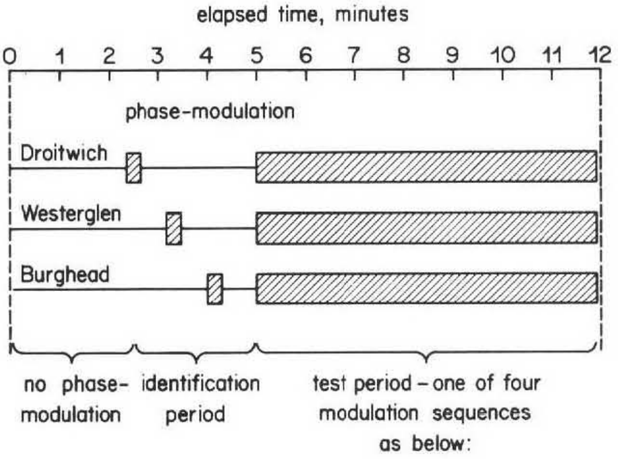


Fig. 7 — The experimental phase-modulation equipment installed at each transmitter for the compatibility tests.

normal (a.m.) programme modulation was present during all of the tests, which were carried out during normal programme hours with the assurance from the results of laboratory tests that little or no annoyance would be caused by the experimental signals, then only in the mush-area where normal reception tends to be poor in any case.



Modulation sequences:

"static" continuous phase-modulation at nominal data-rate.

sequence "1" continuous phase-modulation, timing initially advanced 4 ms then retarded at 20 µs per second.

sequence "2" intermittent phase-modulation: two seconds on then two seconds off.

sequence "3" continuous phase-modulation, timing initially advanced 20 ms then retarded at 100 µs per second.

Fig. 8 — The twelve-minute data-modulation sequences.

3.2. The one-station field test

The purpose of this test was to ascertain the severity of the programme impairment that would be caused in the mush-area in the near worst case conditions obtained by phase-modulating the Droitwich transmitter alone, whilst the other two transmitters in the 200 kHz network transmitted normally. A loop receiving aerial, rotated for best reception at each survey location, was used in order to simulate the case of a domestic portable receiver. The output from the loop aerial was fed to a high-quality monitoring receiver with a good low-frequency response to maximise any frequency impairment that might be introduced by the phase-modulation from Droitwich were made at each of about two hundred locations randomly selected, mainly in the north-western segment of the mush-area on the basis that interference suffered in the other segments would be similar by symmetry. However, a few additional recordings were made at locations in the eastern part of the mush-area where the predicted field strength from the third transmitter at Burghead was known to be relatively higher than in the West due to the high proportion of sea-path, and it was thought that this might influence the results.

The tape-recordings were later analysed and graded by two engineers in a quiet, high-quality listening room according to the CCIR 5-point subjective impairment scale. The results are shown in geographical form in Figure 9, together with the wording of the impairment scale for reference. Figure 9(a) illustrates the general reception impairment in the mush-area when no modulation was present. Any audible impairment to the signal was included in the analysis, including programme-related mush-area interference[2], foreign co-channel interference (which was found to be quite noticeable in the field-strength minima) and interference due to static and radiation from television receivers[7], etc. Thus, at best, the impairment could never be as good as CCIR grade 5 ("imperceptible").

Figure 9(b) illustrates the additional impairment caused when Droitwich alone was phase-modulated. It is clear from these results that, when only one transmitter was modulated, phase-modulation-related impairment could only ever be heard at locations in the area where the audio reception quality was already bad. About ten percent of locations in the area were found to be affected in this way (i.e. the proportion of locations not coded green in Figure 9(b)). which corresponds to less than half of one-percent over the whole of the U.K. In terms of population affected, the corresponding percentage is probably considerably smaller, since both Carlisle and Newcastle are served by m.f. "fill-in" stations for this very reason (see Figure 1).

Both programme and data-related mush-area interference was found to be most prevalent in the Carlisle area which is near to the intersection of the equal fields contour and the line joining Droitwich and Westerglen, the dominant transmitters, as predicted in Section 2.1. There was no indication of any special effect that could be attributed to the presence of signals from Burghead in these one-station tests.

In spite of the good compatibility with existing programme reception when only one station was phase-modulated, as shown by these tests, it was decided that the compatibility needed to be further improved so that no listener would suffer interference from the data signals whatever the orientation of the receiver. It was therefore decided to carry out further field tests in which all three stations were phase-modulated.

3.3. The three-station field tests

Having established the form and distribution of the data-related interference in the mush-area in the one-station tests, the effect of equalising the phase-modulations from all three stations was investigated.

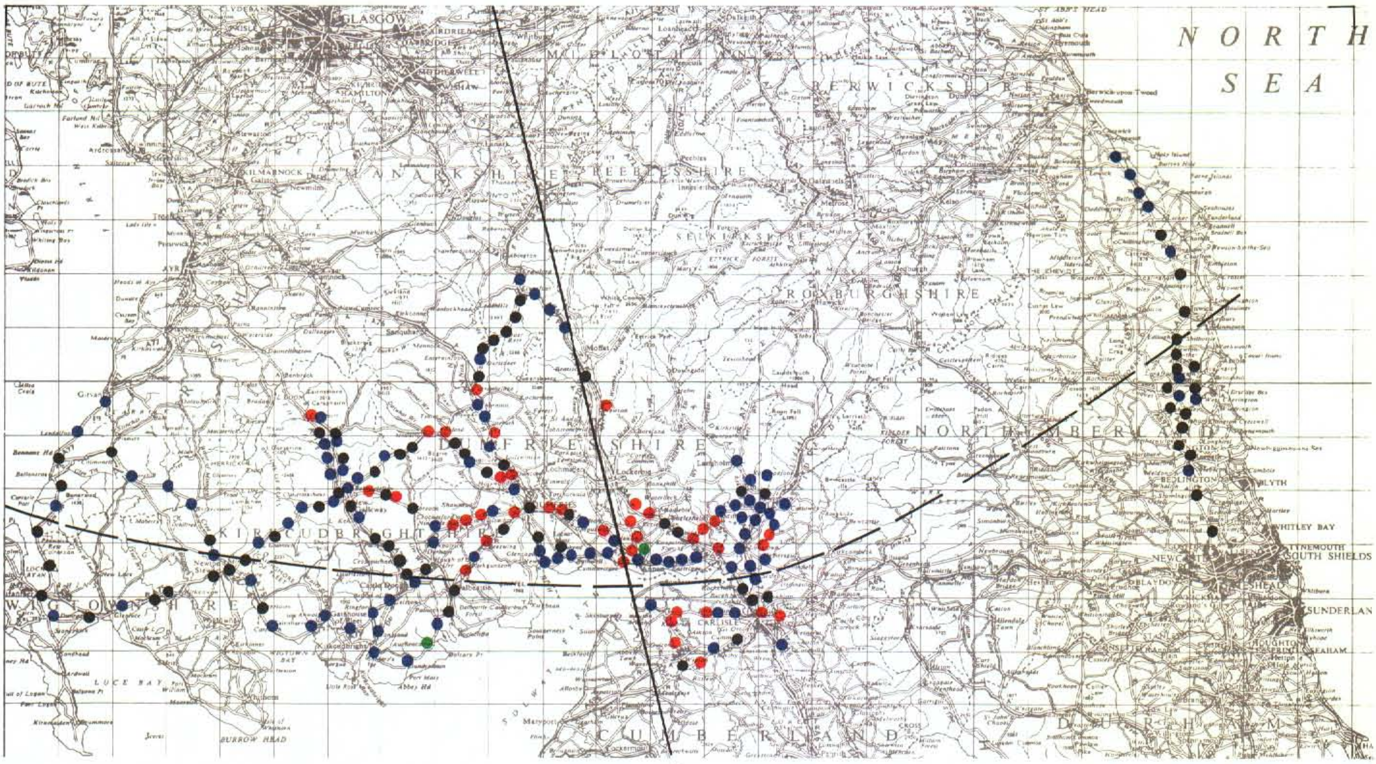
The three-station field tests consisted of, first, a random listening survey similar to that described above, only now concentrating in the area immediately around Carlisle where the interference had earlier been found to be worst. In addition to recording the received audio signal with the loop aerial most favourably orientated, recordings were made at each location with the aerial rotated for minimum signal. In each case the data modulations from each transmitter were identical, and timed such that the two dominant signals in each mush-area arrive in synchronism at the intersection of the equal-fields contour and the line joining the dominant transmitters. The actual timing delays relative to absolute synchronism (defined by the rubidium-controlled clocks - see Section 3.1.) used at each transmitter to achieve this were calculated in terms of free-space propagation and are listed below:

Transmitter	Data timing delay
Droitwich	0.00 ms
Westerglen	0.57 ms
Burghead	0.64 ms

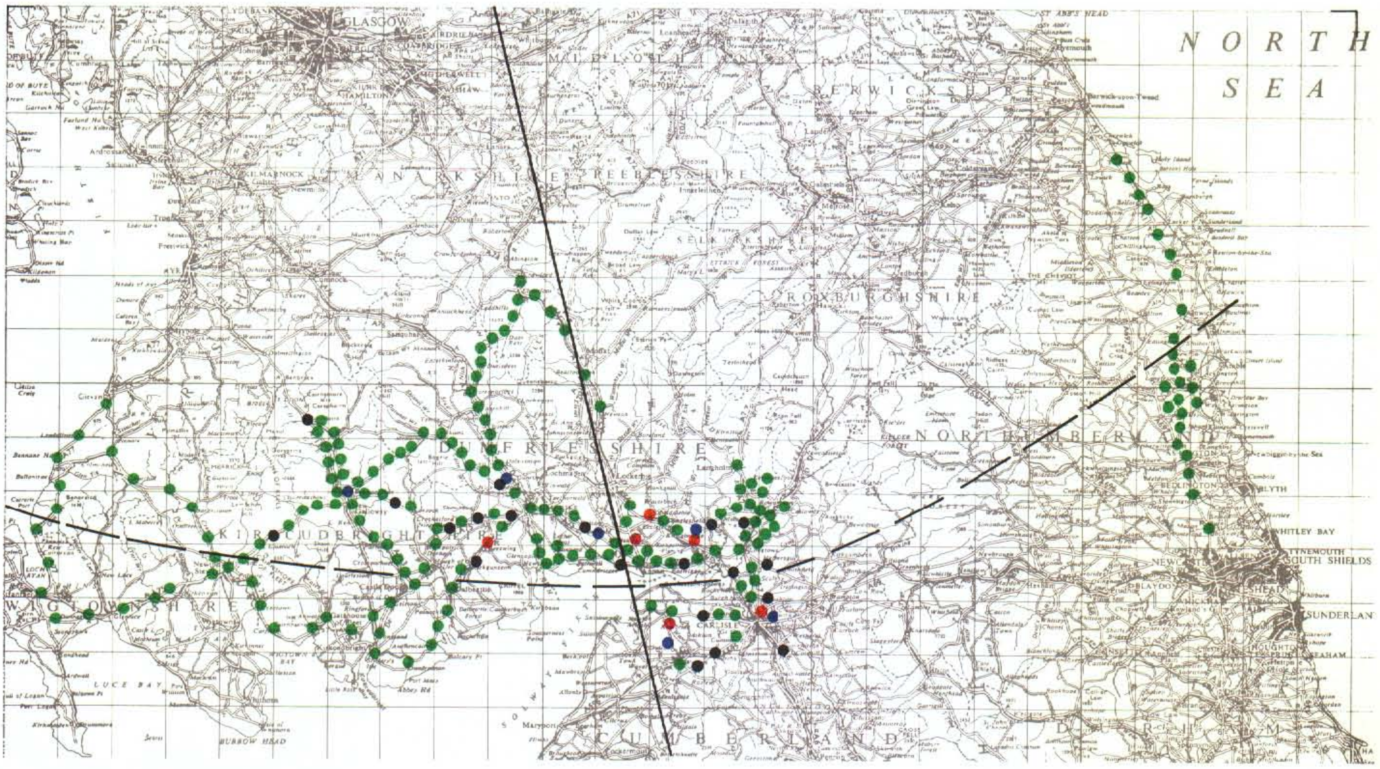
Maps showing the results of the three-station listening survey are given in Figures 10 and 11. Figures 10(a) and 11(a) give a measure of the existing programme impairment, whilst 10(b) and 11(b) show the additional impairment due to the data-signal. The value of synchronising the data modulations from all three stations is immediately obvious; at only one location and then with the aerial rotated unfavourably so that the normal programme reception was very poor, was there any suggestion of audible interference from the data signal. These results clearly show that the proposed data modulation parameters[1] are wholly compatible with programme reception in all parts of the mush-area.

3.3.1. Data signal modulation timing

The worst-case effect of changing the data modulation timing at one of the transmitters with respect to that at the others, was investigated at fifteen locations shown on the map in Figure 12. At each of these locations, which were selected to be near to a minimum of field-strength, the receiving aerials was rotated for worst programme



(a). *existing programme impairment (no phase-modulation)*

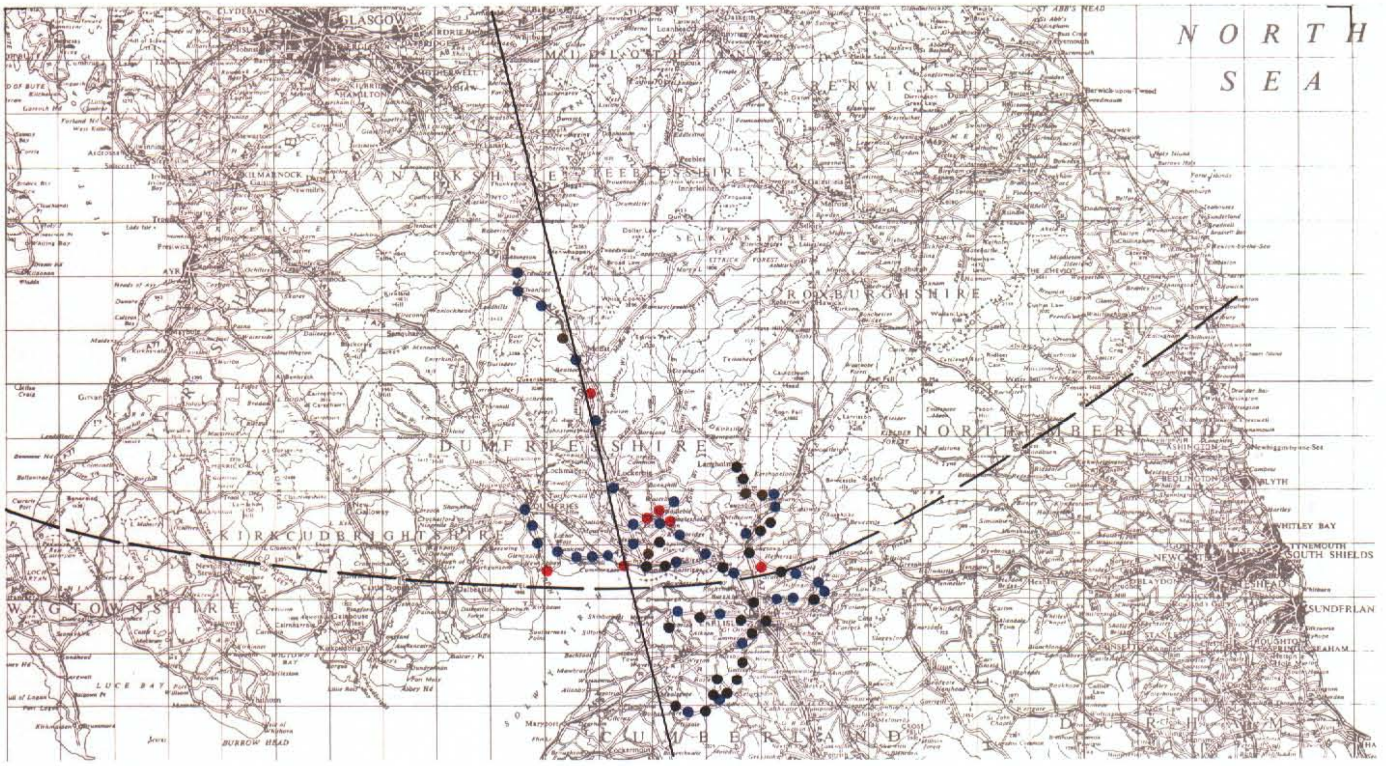


(b). *additional impairment due to phase-modulation*

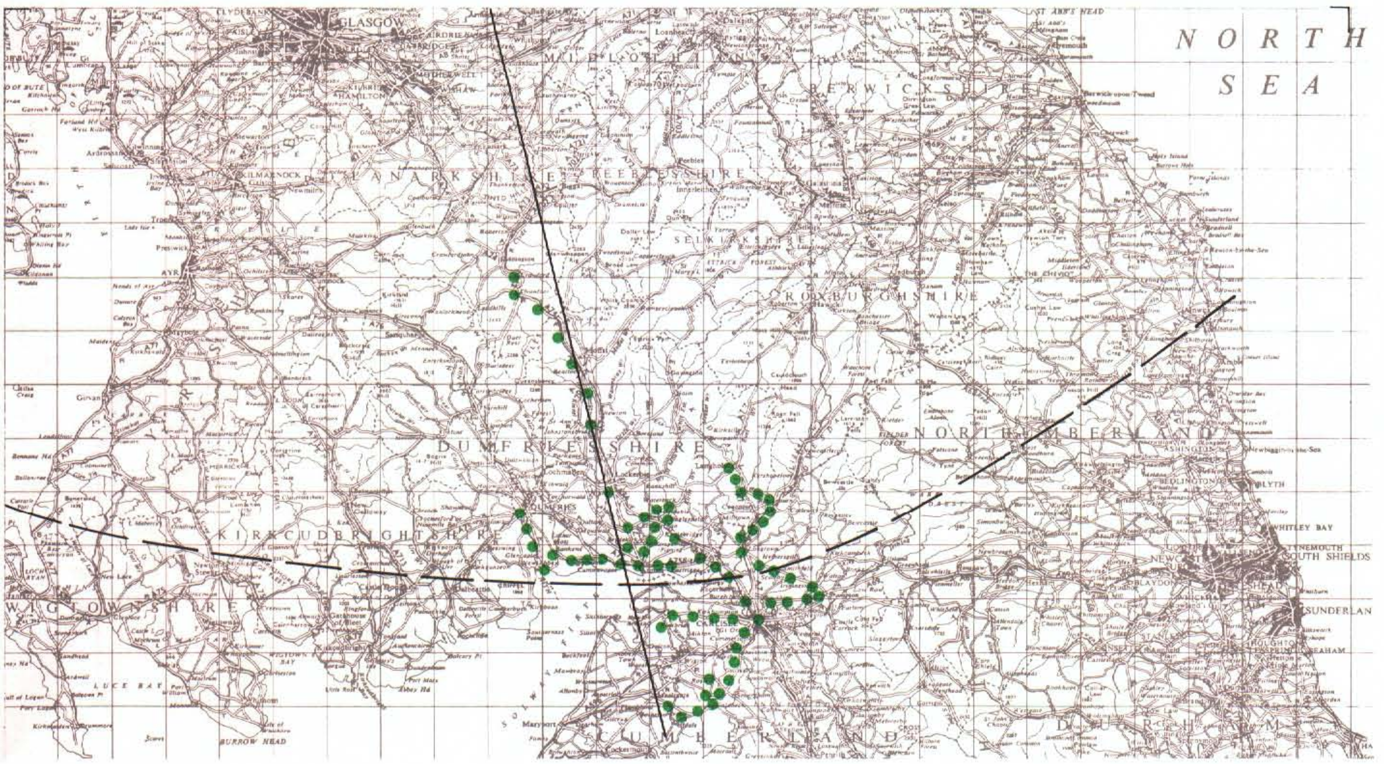
Fig. 9 — The compatibility results with only Droitwich phase-modulated: aerial rotated for maximum signal.

CCIR 5 - point impairment scale: **● 5 imperceptible, ● 4 perceptible but not annoying, ● 3 slightly annoying, ● 2 annoying, ● 1 very annoying.**

———— line joining Droitwich and Westerglen. —— —— equal fields contour from Droitwich and Westerglen.



(a). existing programme impairment (no phase-modulation)

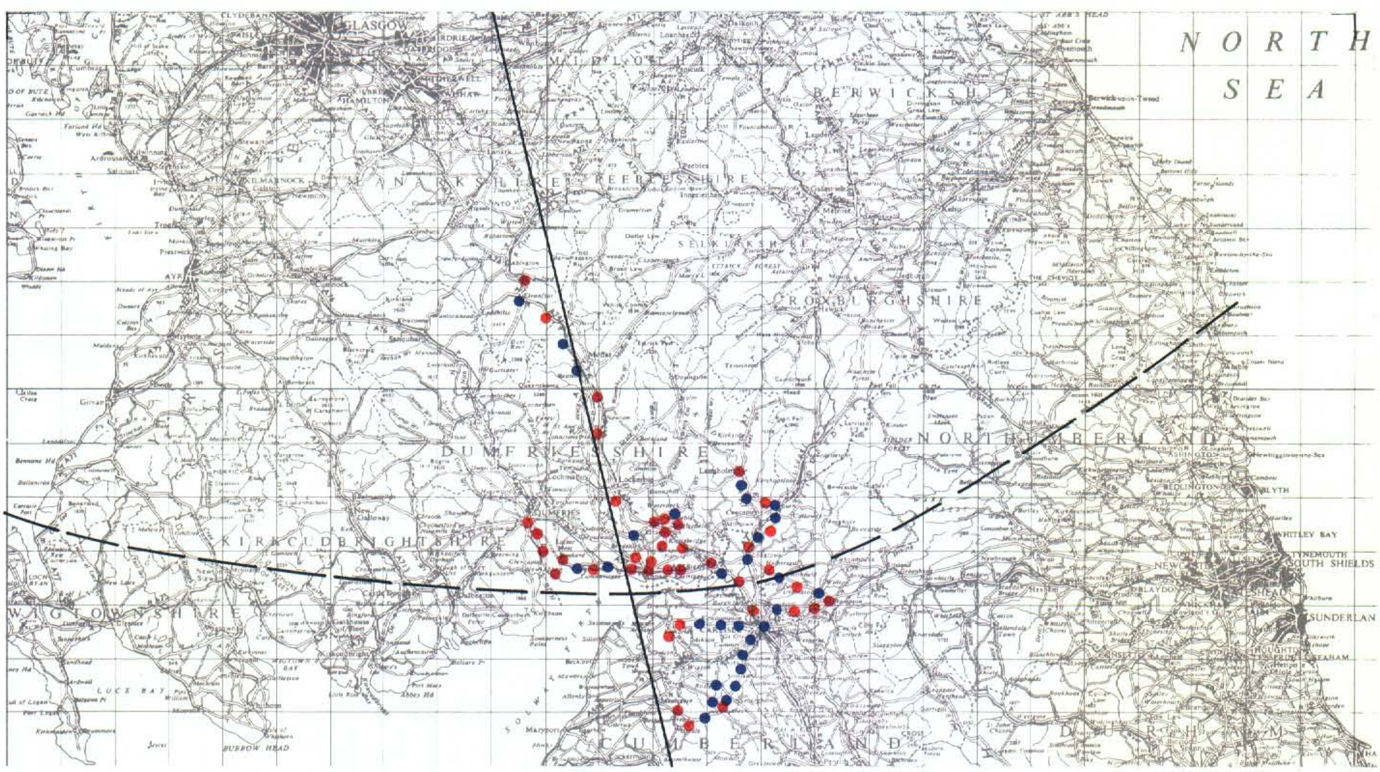


(b). additional impairment due to phase-modulation

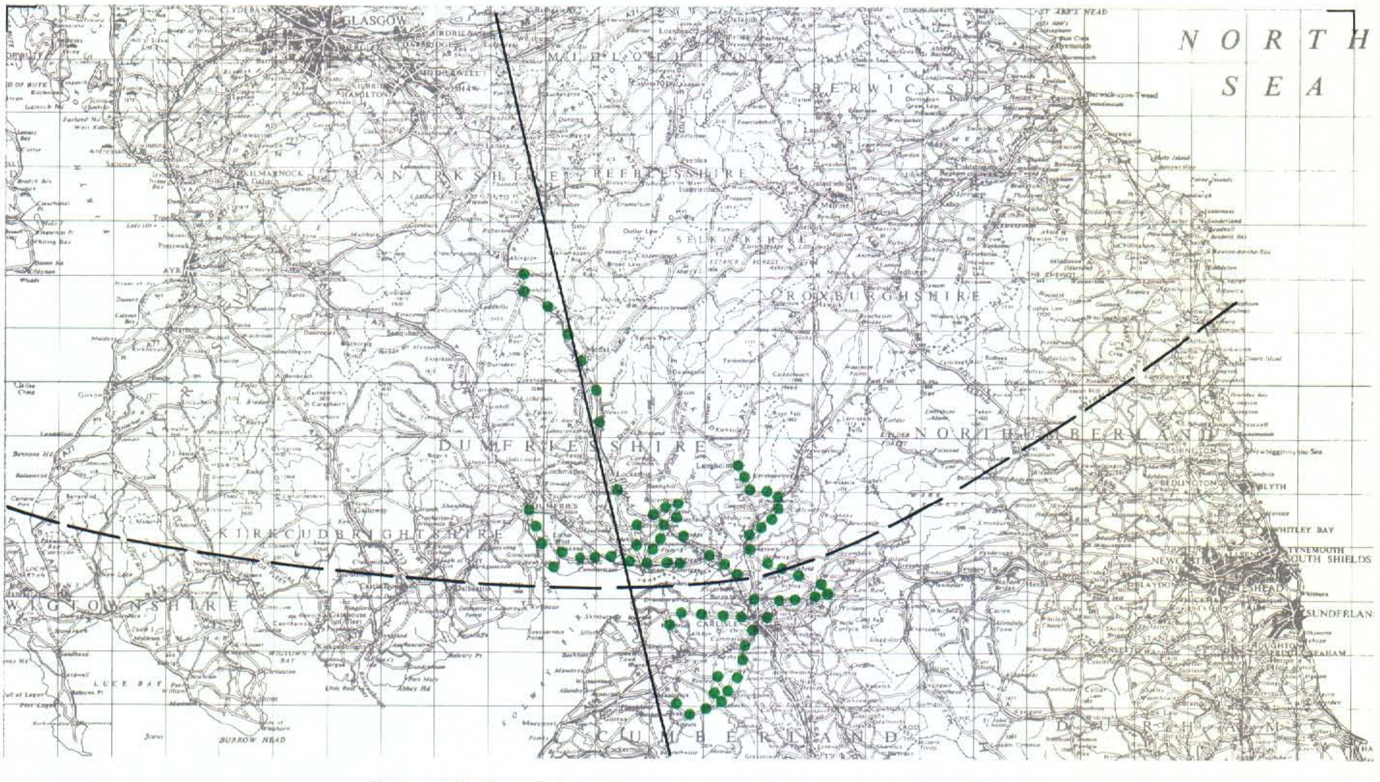
Fig. 10 – Droitwich, Westerglen and Burghead phase-modulated in synchronism: aerial rotated for maximum signal.

CCIR 5 - point impairment scale: **● 5 imperceptible, ● 4 perceptible but not annoying, ● 3 slightly annoying, ● 2 annoying, ● 1 very annoying.**

——— line joining Droitwich and Westerglen. — — equal fields contour from Droitwich and Westerglen.



(a). *existing programme impairment (no phase-modulation)*

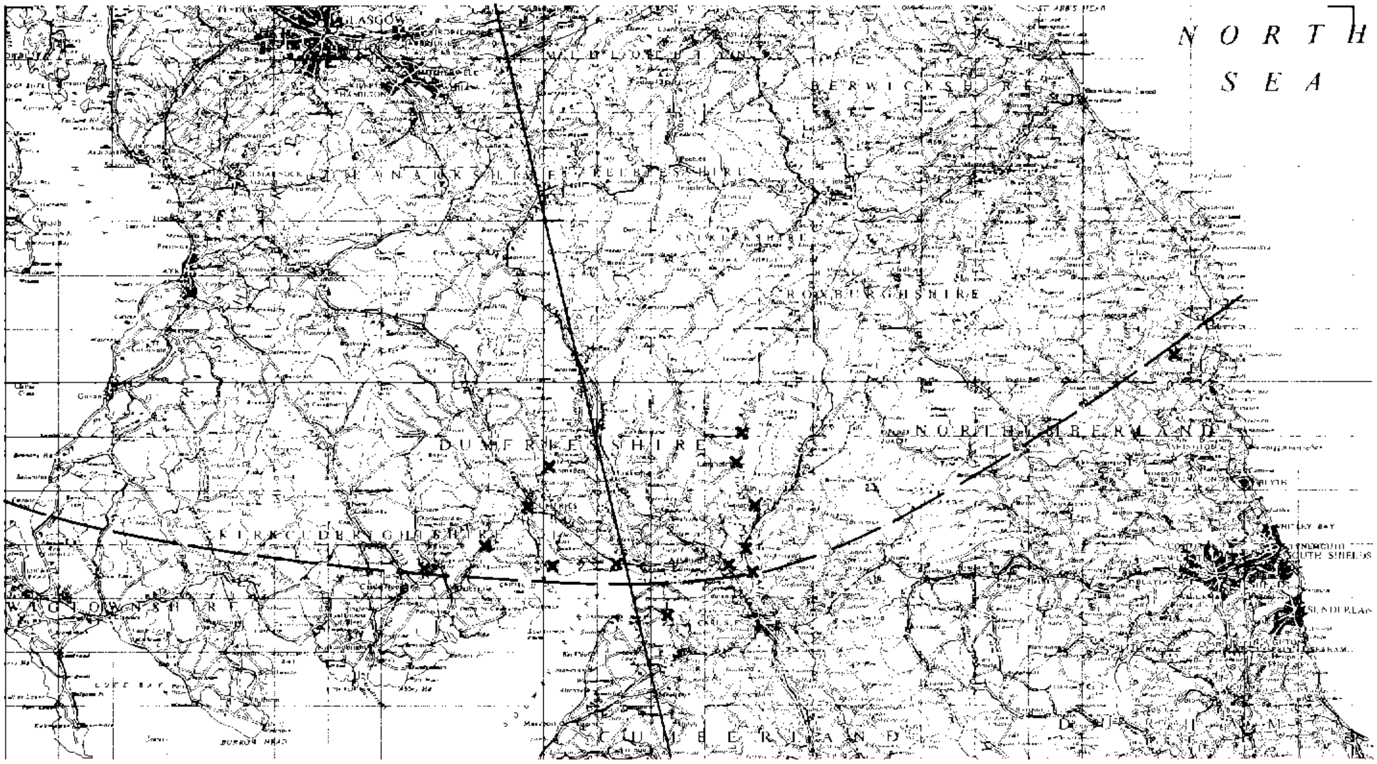


(b). *additional impairment due to phase-modulation*

Fig. 11 – Droitwich, Westerglen and Burghead phase-modulated in synchronism: aerial rotated for minimum signal.

CCIR 5 - point impairment scale: **● 5 imperceptible, ● 4 perceptible but not annoying, ● 3 slightly annoying, ● 2 annoying, ● 1 very annoying.**

———— line joining Droitwich and Westerglen. **— — equal fields contour from Droitwich and Westerglen.**



——— line joining Droitwich and Westerglen. — — — equal fields contour from Droitwich and Westerglen.

Fig. 12 - The locations where timing-sweep tests were carried out.

reception and a tape recording was made whilst the timing of the data modulation from one of the stations was slowly varied about its nominal value. This was achieved, for example, by selecting modulation sequence "static" at Droitwich and Burghead, and modulation sequence "3" at Westerglen (see Figure 8), so that the data signal timing from Westerglen would vary progressively from + 20 ms to − 20 ms over the seven-minute test period. The position in the sequence, and thus the current value of mis-timing, was identified using a fifth clock in the survey vehicle, and recording the identification signals derived from it along with the received audio signal. The recordings were later analysed under listening room conditions in order to detect at what point in the sequence the data-related interference became just perceptible.

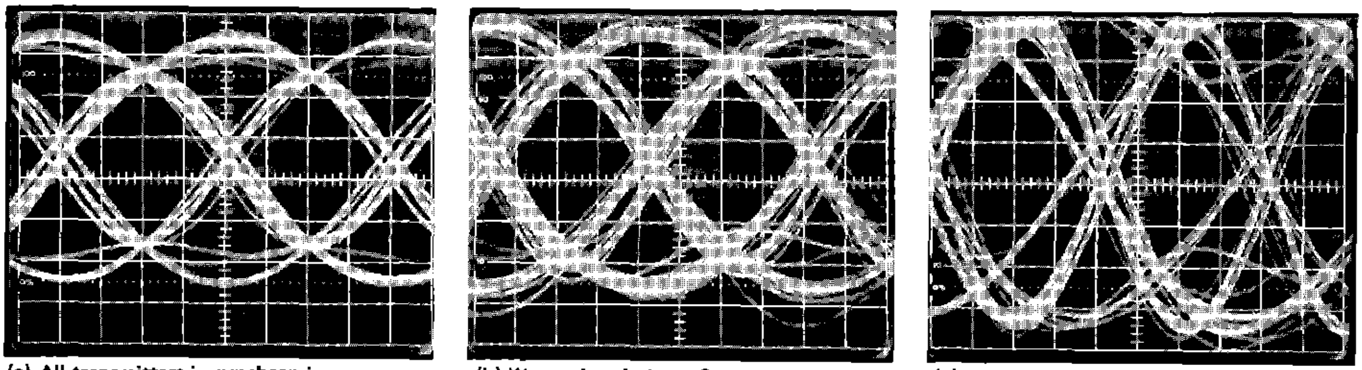
For most of the recordings, the timing of the data signal modulation from Westerglen was varied whilst that of the other two stations remained static. The results of these tests show that related interference was never perceptible for data mis-timings of less than ± 2 ms (or within one-tenth of a data signal bit-cell).

A few recordings were made in which the timing of the data signal modulation from Burghead was also varied with respect to the other two. In none of these recordings was any related interference heard at all, even though the data timing at Burghead was made to traverse two complete data bit-cell periods. This would indicate that the effect of a third transmitter can be ignored when planning the delay-equalisation of the data signal - it is sufficient to consider only the timings of the two data signals carried by the dominant transmitters in each mush-area.

However, the effect of the third transmitter was obvious in other ways. In particular, it was required in this part of the tests to seek out areas of fairly deep field-strength minima in order to find a worst-case. It was found that, in some areas which were known to be near both to the equal fields contour and the line joining the dominant transmitters, deep minima (greater than 20 dB below the average) did not occur, whilst they did occur in other areas several wavelengths away. This finding supports the prediction of Figure 6.

Moreover, locations were found near to Carlisle where, without phase-modulation, the received audio signal exhibited a distinct "drain-pipe" quality which is known to be typical of gross programme modulation mis-timing[2]. This effect could be attributed only to a non-negligible contribution from the programme signal

Receiver Location 1

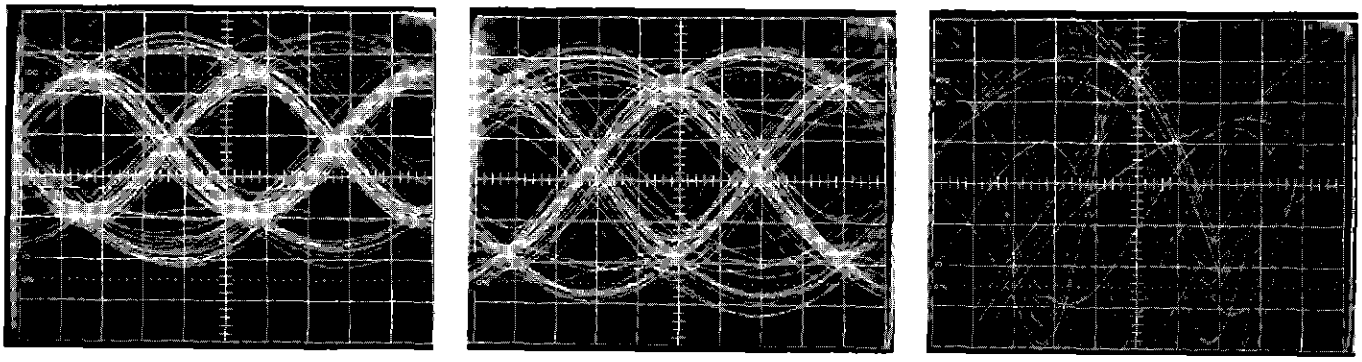


(a) All transmitters in synchromism
Measured eye-height 92%.

(b) Westerglen timing + 2 ms
Measured eye-height 80%.

(c) Westerglen timing + 4 ms
Measured eye-height 70%.

Receiver Location 2

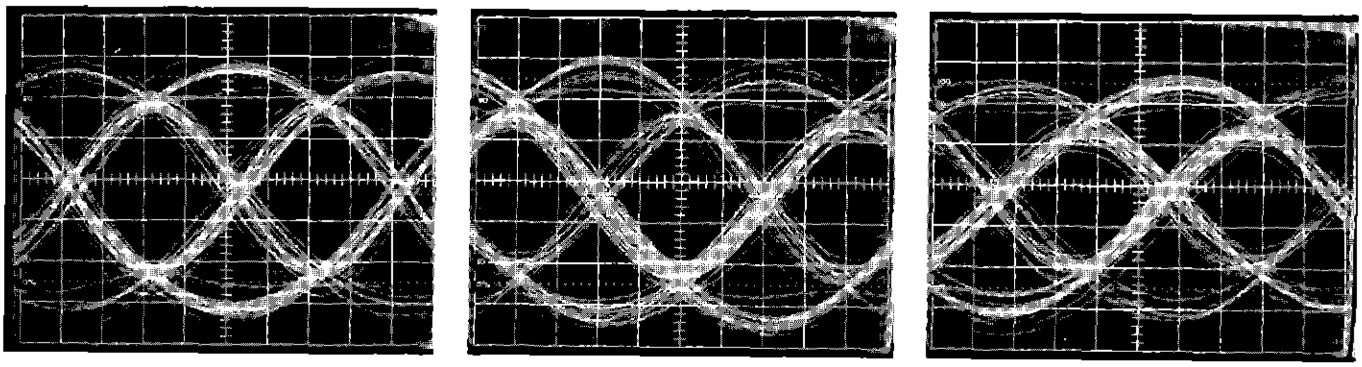


(d) All transmitters in synchronism
Measured eye-height 66%.

(e) Westerglen timing + 2 ms
Measured eye-height 57%.

(f) Westerglen timing + 4 ms
Measured eye-height 0%.

Receiver Location 3



(g) All transmitters in synchronism
Measured eye-height 81%.

(h) Burghead timing + 10 ms
Measured eye-height 78%.

(i) Burghead timing + 20 ms
Measured eye-height 68%.

Fig. 13 - Data eye-patterns for reception in the mush-area when either the timing of the data signal from the Westerglen transmitter, or that from the Burghead transmitter is varied with respect to the others. "Eye-height" is here the quotient of the measured mimimum and average peak-to-peak data waveform amplitudes at the sampling instants defined by the survey vehicle's "clock".

modulation carried by the Burghead signal, since the programme modulations from Westerglen and Droitwich were delay-equalised for the tests. However, it was outside the scope of the work to investigate this effect in any greater detail.

3.3.2. Data reception

During the timing-sweep tests it was possible to record the received data eye-height under various conditions. "Eye-height" is a measure of the integrity of the received data signal and is here defined as the ratio of the minimum peak-to-peak excursion of the demodulated data signal waveform at the correct sampling instants to the average excursion at those instants, expressed as a percentage. To obtain the oscillograms showing eye-height given in Figure 13, the demodulated data waveform was observed on a digital storage oscilloscope triggered by a bit-rate clocking signal (50 Hz) derived from the survey vehicle clock. A long-exposed photograph was then taken of the display so as to include many excursions of the data signal. Eye-height photographs were recorded at about twenty locations, each chosen, as before, for poor reception quality, but only three of the worst cases are reproduced in Figure 13. In the first two cases, the timing of the data signal modulation at Westerglen was varied by the amounts shown relative to the other two stations, whilst in the third case the timing of Burghead's modulation was varied. In each case, the height picture on the left is for all three stations in nominal synchronism. It is clear from these pictures, which are typical of worst-case reception in the mush-area, that a timing tolerance of better than ± 2 ms (as required for programme compatibility above) is adequate also for data reception.

The third set of eye-heights, Figure 13(g) to (i), show that the effect of gross mistiming of the modulation of the third station in a mush-area is measurable but small in terms of closing the data "eye". In most of the eye-height measurements taken (not shown in Figure 13) the effect of the third station was negligible.

4. Conclusions

The data transmission parameters proposed were found to be wholly compatible with programme reception throughout the mush-areas, providing all three stations in the co-channel network carried identical data signal modulation and the data signal modulation timings of the two main received signals in each mush-area were synchronised to better than ± 2 ms. Within this tolerance, data reception in the mush-areas was also found to suffer negligible additional degradation.

Given a near worst-case condition, in which only one of the main signals was phase-modulated, the resulting programme impairment was evident only when the received programme quality itself was already poor due to normal mush-area impairments or receiver misorientation.

The quality of the receiving equipment used in the field tests exceeded that normally used by the public, and recorded excerpts were analysed in a quiet, high-quality listening room in order to highlight any impairments. The results are therefore safe, in that the average listener would hear less impairment due to phase-modulation than that observed.

5. The future

Having demonstrated the viability of the proposed l.f. data transmission system, consideration is now being given to optimising the format of the transmitted data signal whilst preserving the basic signal parameters now supported by the results of the field tests.

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